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Received: 2017-11-21 ; Accepted: 2018-01-23

A METHOD TO ASSESS RELIABILITY OF SEASONALLY OPERATED MACHINES USING FUZZY LOGIC PRINCIPLES

Summary

The aim of this study was to develop an original method, which would objectively quantify reliability of seasonally operated machines. The method uses an algebraic deduction model and fuzzy logic algorithms facilitating simulation studies. The assessment of machine reliability provides the index of reliability I_R, which is based on a set of adopted criteria. An additional objective for the authors was to empirically verify the developed method based on seasonally operated agricultural machines. Values of index of reliability I_R fall within the range of 0.647-0.725, depending on the type of tested machines. In accordance with the adopted criteria of linguistic synthesis the obtained values of the index I_R indicate high reliability of tested machines.
***Key words**: machine reliability, machine operation, AHP, fuzzy logic, technical servicing*

METODA OCENY NIEZAWODNOŚCI MASZYN PRACUJĄCYCH SEZONOWO Z WYKORZYSTANIEM REGUŁ WNIOSKOWANIA ROZMYTEGO

Streszczenie

Celem pracy było opracowanie oryginalnej metody, która w obiektywny sposób kwantyfikuje niezawodność maszyn pracujących sezonowo. Metoda wykorzystuje algebraiczny model dedukcyjny oraz algorytmy logiki rozmytej, które umożliwiają przeprowadzenie badań symulacyjnych. Efektem oceny niezawodności maszyn jest wyznaczenie wskaźnika niezawodności I_R, który bazuje na zbiorze przyjętych kryteriów. Dodatkowym zamierzeniem autorów była empiryczna weryfikacji opracowanej metody na przykładzie maszyn rolniczych pracujących sezonowo. Wartości wskaźnika niezawodności I_R zawierają się w przedziale 0,647-0,725, w zależności od typu badanych maszyn. Zgodnie z przyjętymi kryteriami oceny lingwistycznej wyznaczone wartości wskaźnika I_R świadczą o wysokiej niezawodności badanych maszyn.
***Słowa kluczowe**: niezawodność maszyn, eksploatacja maszyn, AHP, logika rozmyta, serwisowanie techniczne*

1. Introduction

A characteristic feature of operation of agricultural machines is connected with the seasonal character of their use. This means that most agricultural machines are used only to a limited extent in comparison to their potential work time. For this reason agricultural machines should have considerable reliability, which is connected with the need of timely performance of frequently complex production processes in agriculture.

Nevertheless with the passing time various types of wear occur, which are caused by physical aging of machines. The rate of physical aging of machines depends on their quality, intensity of their use, work and storage conditions.

Most agricultural machines are mobile machines, which travel in fields and on roads of various types, and as a result frequently change speed and direction of movement. Work conditions of these machines also vary greatly, e.g. crop height, soil moisture content, amount and type of contamination, operating resistance, etc. As a result of all these factors these machines are exposed to various loads, which intensify fatigue wear. Moreover, in many cases we observe exceeded permissible stresses and average damage [10, 22].

The seasonal character of work in the case of agricultural machines and the resulting long idle periods do not lead to the elimination of the technical servicing. A considerable role in the slowing of the physical aging processes is played by conditions of machine storage. It is best to keep machines in places where the effect of weather conditions, such as changes in temperature and humidity, etc., is eliminated. Only the most expensive machines are stored in such a manner, while the others are exposed to weather conditions. Frequently during machine storage aging processes are progressing as a result of weather-related corrosion, consisting mainly in electrochemical and chemical corrosion [10, 22].

Cultivation technologies require the use of machine aggregates comprising several types of machines. They are mostly series systems, thus damage to one machine frequently causes down time in the other machines, contained in the aggregate. This may be prevented using machines of high reliability. Such a reliability should be ensured by high quality machine manufacturing as well as timely and comprehensive technical servicing [10].

The above-mentioned and characterised operating conditions for agricultural machines are objective reality and have a varied effect on their reliability.

As it was stated by Macha [18], when fitness for use of a machine is required in the interval *(0,t)*, which measure may be time, the amount of performed work, the number of performed operations, the length of covered distance, then reliability is the probability that values of parameters defining significant properties of the machine in period *(0,t)* do not exceed admissible boundaries under specific conditions of its operation. In the probabilistic sense reliability of a machine $R(t)$ at a given moment t is probability $P(T \geq t)$ that its durability T is greater than t, equation 1:

$$R(t) = P(T \geq t) \quad (1)$$

where: durability T may be expressed in time in *[s]*, area in *[ha]*, length in *[km]*.

One of the methods to characterise the capacity to meet the requirements is to give the probability that a machine, which meets the requirements at a given t, e.g. at a given time t, in the next interval dt or Δt will cease to meet them. It is considered what part of objects, which remained fit (in working order) in the interval $(0, t)$, will probably be unfit (not in working order) in the interval $(t, t+dt)$. This unfit part of objects is denoted by $\lambda(t)dt$, while $\lambda(t)$ is called the function of risk, the function of depletion intensity or the function of damage intensity. The value of this function is referred to as risk, depletion intensity and damage intensity. When $\lambda(t)$ increases, risk (depletion or damage intensity) increases – reliability properties of objects deteriorate. When $\lambda(t)$ decreases, reliability properties of objects improve. Within each successive intervalΔt a lesser percentage of unfit objects is eliminated from the set of fit objects [1, 4, 5, 11, 16, 26, 28, 31, 32, 33, 34, 35].

The concept of f*uzzy sets* was introduced by an American researcher Zadeh [36] in 1965 in order to model complex processes. The main part of the theory of fuzzy sets is *fuzzy logic* applied in system modelling and control [3, 6, 7, 8, 9, 12, 15, 17, 19, 20, 21, 27, 28, 29, 30, 36, 37, 38]. The primary concept in the theory of sets, apart from set A_i, is the relation of the element belonging to set ($x \in A_i$). In contrast to sets with non-fuzzy belonging in fuzzy sets there no definite boundaries between elements, which belong to a given set and those, which belong to other sets. In such a case the degree of belonging of an element to the set is rather determined, i.e. a number from interval *[0,1]*. Each variable x, which is treated as a real number ($x \in R^n$) may be assigned another value of the function of belonging to set A_i. A fuzzy set A_i is characterised by the function of belonging $\mu_{Ai}(x)$, assuming a value from interval [*0,1*] and defining the degree of belonging of a variable to a fuzzy set A_i. Thus the fuzzy set may be characterised as a set of ordered pairs $(x, \mu_{A_i}(x))$.

Condition $\mu_{A_i}(x_i) = 1$ denotes complete belonging of xi to set A_i, i.e. $x_i \in A_i$. In turn, condition $\mu_{A_i}(x_i) = 0$ denotes a lack of such belonging, $x_i \notin A_i$. Intermediate values $\mu_{A_i}(x_i)$ express partial belonging of xi to set A_i.

2. Aim and scope of study

The aim of this study is to develop a method to determine the index of reliability I_R for seasonally operated machines, based on a set of adopted assessment criteria. The basic assumptions of this method include multiple criteria, efficient and objectivity. The developed method comprises an algebraic deduction model, constituting a procedure to quantify reliability of seasonally operated machines as well as an algorithm facilitating simulation studies, which quantify reliability of tested machines.

The main stage in the process of method development is to construct a structural model, which will take an algebraic form (a mathematical algorithm) making it possible to express the level of reliability of seasonally operated agricultural machines in the numerical form of a value of index I_R.

3. Theoretical foundations of the method assessing machine reliability

Reliability of seasonally operated machines, due to a series of variables, which may influence it, may be presented in the form of a composite function, which is expressed using equation 2:

$$I_R = f[r(E_i), w(K_i), \mu_{A_i}(\overline{x_i})], \quad (2)$$

where:
I_R – index of reliability of seasonally operated machines,
f – a composite function of linguistic syntheses of machine reliability by their users r, weights of main criteria w and the degree of belonging μ_A , the crip numerical input value $\overline{x_i}$ of a fuzzy set A_i of main criteria K_i,
r – a function of variables of linguistic syntheses of machine reliability machines by their users E_i,
w – a function of variables of main criteria K_i,
$\mu_{A_i}(\overline{x_i})$ – the degree of belonging of the crip numerical input value $\overline{x_i}$ of a fuzzy set A_i of main criteria K_i.

The value of I_R in the proposed method to assess reliability of seasonally operated machines is calculated in two stages:
Stage I – assigning weights to criteria and collection of linguistic syntheses of machine reliability by their users,
Stage II – determination of index I_R using a fuzzy model.

The construction of the method to assess reliability of seasonally operated machines was initiated by defining assessment criteria and their relationships. In the presented model the result of reliability assessment, in the form of index I_R, is determined by the length of the operating period of a machine in season K_1, operating conditions of machine K_2, conditions of its storage K_3, knowledge and skills of machine operator K_4 and quality of its servicing K_5.

Weight of individual criteria was determined using the Analytic Hierarchy Process *(AHP)*. This method is a heuristic approach developed by an American researcher Saaty [25, 26, 27] and combining elements of mathematics and psychology. The hierarchy process for criteria assessing the reliability of seasonally operated machines is conducted individually by each machine user.

In the developed method compared criteria are not measurable. For this reason a linguistic approach is applied, based on the theory of fuzzy sets. A linguistic variable assumes then verbal descriptors as its values (e.g.: a short operation time to first failure, good machine storage conditions, extensive knowledge of the operator, high quality of technical servicing). The 9-point preference scale adopted by Saaty [25, 26, 27] may be adapted to the current needs resulting from the number of adopted criteria.

If by the decision of the machine user criterion K_i is more important than criterion K_j, the assessment a_{ij} determined in this pair of criteria takes the following values:
- 1, if K_i and K_j are equally important,
- 3, if K_i is slightly more important than K_j,
- 5, if K_i is much more important than K_j,
- 7, if K_i is markedly more important than K_j,

- 9, if K_i is absolutely more important than K_j,
- 2, 4, 6, 8 intermediate values between the above-mentioned situations.

Determined assessments comprise a matrix comparisons $K_{nn}^{(U)}$ of $n \cdot n$, where *n* is the number of all compared criteria. They are ordered successively in headings of rows and columns of the matrix. Its elements include assessments a_{ij}, entered at the intersection of *i*-th row with *j*-th column, [25, 26, 27].

$$\begin{array}{c|c} & \begin{array}{cccccc} K_1 & K_2 & \dots & K_j & \dots & K_n \end{array} \\ \hline \begin{array}{c} K_1 \\ K_2 \\ \vdots \\ K_i \\ \vdots \\ K_n \end{array} & \begin{bmatrix} a_{11}=1 & a_{12} & \dots & a_{1j} & \dots & a_{1n} \\ a_{21} & a_{22}=1 & \dots & a_{2j} & \dots & a_{2n} \\ \vdots & \vdots & & \vdots & & \vdots \\ a_{i1} & a_{i2} & \dots & a_{ij}=1 & \dots & a_{in} \\ \vdots & \vdots & & \vdots & & \vdots \\ a_{n1} & a_{n2} & \dots & a_{nj} & \dots & a_{nn}=1 \end{bmatrix} = K_{nn}^{(U)}, \end{array} \tag{3}$$

where: *i, j = 1, 2, ..., n.*

Matrices $K_{nn}^{(U)}$, for *U = 1, 2, ..., n*, are matrices of comparisons by pairs of criteria adopted in the assessment of reliability of seasonally operated machines. Each of the matrices of pair-wise comparisons should meet condition 4:

$$a_{ij} = \frac{1}{a_{ji}}, \tag{4}$$

where: *i, j = 1, 2, ..., n.*

For each matrix of pair-wise comparisons the procedure of individual ranking of adopted criteria assessing reliability consists in column normalisation of matrix $K_{nn}^{(U)} = [a_{ij}]$, to matrix [25, 26, 27].

$$\begin{array}{c|c} & \begin{array}{cccccc} K_1 & K_2 & \dots & K_j & \dots & K_n \end{array} \\ \hline \begin{array}{c} K_1 \\ K_2 \\ \vdots \\ K_i \\ \vdots \\ K_n \end{array} & \begin{bmatrix} \bar{a}_{11}=1 & \bar{a}_{12} & \dots & \bar{a}_{1j} & \dots & \bar{a}_{1n} \\ \bar{a}_{21} & \bar{a}_{22}=1 & \dots & \bar{a}_{2j} & \dots & \bar{a}_{2n} \\ \vdots & \vdots & & \vdots & & \vdots \\ \bar{a}_{i1} & \bar{a}_{i2} & \dots & \bar{a}_{ij}=1 & \dots & \bar{a}_{in} \\ \vdots & \vdots & & \vdots & & \vdots \\ \bar{a}_{n1} & \bar{a}_{n2} & \dots & \bar{a}_{nj} & \dots & \bar{a}_{nn}=1 \end{bmatrix} = \overline{K}_{nn}^{(U)}, \end{array} \tag{5}$$

where:

$$\bar{a}_{ij} = \frac{a_{ij}}{\sum_{i=1}^{n} a_{ij}}, \tag{6}$$

Next mean values of weights of criteria w_{K_i} are established in each row of the normalised matrix $\overline{K}_{nn}^{(U)}$, according to equation 7:

$$w_{K_i} = \frac{\sum_{i=1}^{n} \bar{a}_{ij}}{m}, \tag{7}$$

where: *i, j = 1, 2, ..., m.*

The value of weight $w_{K_{ij}}$ indicates the position of criterion K_i in the individual ranking in relation to the other criteria of assessment of machine reliability. As a result of the above calculations each criterion has as many different weights w_{K_i} as many machine users participated in the study. Thus it is necessary to determine the global weight $w_{K_i}^{(G)}$ for criterion K_i of quality assessment, which may be obtained using the equation:

$$w_{K_i}^{(G)} = \frac{\sum_{j=1}^{Ui} w_{K_i},}{n_{U_i}} \tag{8}$$

where:

n_{U_i} is the number of machine users participating in the study.

Global weights $w_{K_i}^{(G)}$ facilitate hierarchisation of criteria K_i and are the starting point in the design of a fuzzy model of the system assessing machine reliability, since they are represented by input fuzzy sets A_i.

A fuzzy set A_i in the method to assess reliability of seasonally operated machines in a certain non-empty space $X = \{\bar{x}\}$ is referred to as a set ordered pairs:

$$A_i = \{(\bar{x}, \mu_{A_i}(\bar{x})); \bar{x} \in X\} \tag{9}$$

where:

$\mu_{A_i} : X \to [0,1]$ is the function belonging to a fuzzy set $A_i \subseteq X$. This function ascribes to each element $\bar{x} \in X$, its degree of belonging to a fuzzy set A_i.

Depending on the value of the degree of belonging $\mu_{A_i}(\bar{x})$, we may distinguish:

1) $\mu_{A_i}(\bar{x}) = 1$ denotes complete belonging of element $\bar{x}$ to a fuzzy set A_i, i.e. $\bar{x} \in A_i$,

2) $\mu_{A_i}(\bar{x}) = 0$ denotes a lack of belonging of element $\bar{x}$ to a fuzzy set A_i, i.e. $\bar{x} \notin A_i$,

3) $0 < \mu_{A_i}(\bar{x}) < 1$ denotes partial belonging of element $\bar{x}$ to a fuzzy set A_i.

Input and output values and variables of fuzzy sets do not have to be numerical values, but they may also be linguistic variables (assessments). They are expressed in linguistic values or fuzzy numbers. A linguistic value is an assessment of linguistic variables expressed in words - very high, high, medium, low, very low reliability of machines. A fuzzy number informs to what degree it deviates from the definite crip numerical value, e.g. time of failure-free operation of a cereal combine harvester was approx. 100 h, repair time of an engine is approx. 10 h, appropriate engine oil temperature is approx. 90°C.

A fuzzy model for the method assessing reliability of seasonally operated machines is composed of three basic blocks: fuzzification, inference and defuzzification, comprising a joint structure (Fig. 1).

At the input to the fuzzy system it is necessary to define the shape of the function of belonging, reflecting the area of considerations X on the closed interval *<0;1>*. The input set A of the fuzzy model the method assessing reliability of seasonally operated machines will comprise 5 terms (Fig. 2). Each of them expresses a linguistic assessment of adopted criteria: set *A-I* – very low, set *A-II* – low, set *A-III* – medium, set *A-IV* – high and set *A-V* – very high.

In the fuzzy model of the proposed method assessing reliability of seasonally operated machines the established input sets A need to be modified using values of global weights of criteria, assigned to them by machine users $W_{K_i}^{(G)}$ Modification of input sets of individual criteria for assessment consists in their shift towards the axis of values of the function of belonging $\mu_A(x_i)$, by the value of weight $W_{K_i}^{(G)}$ [13, 14].

The shift of input sets A by the value of weight $W_{K_i}^{(G)}$ makes it possible to include the hierarchisation of criteria for assessment of machine reliability and determine new input sets $\overline{A}$ (Fig. 3). Crip numerical values $\overline{x}_i$, for criteria of assessment with greater weight will then obtain a greater degree of belonging in the module of fuzzification in the fuzzy model of this method [13, 14].

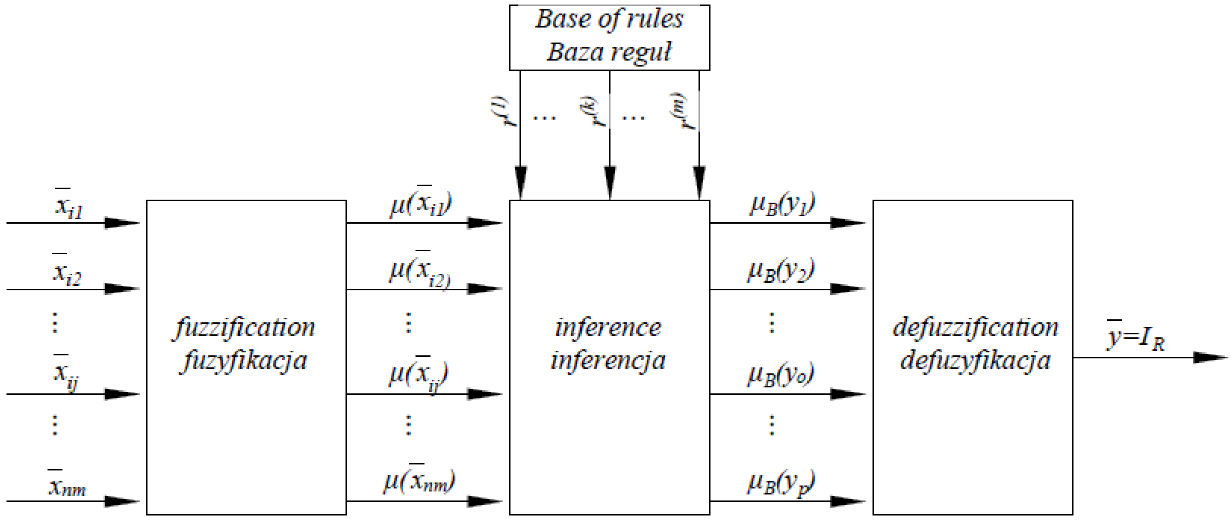

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Fig. 1. Structure of a fuzzy model of the method assessing reliability of seasonally operated machines
Rys. 1. Struktura modelu rozmytego metody oceny niezawodności maszyn pracujących sezonowo

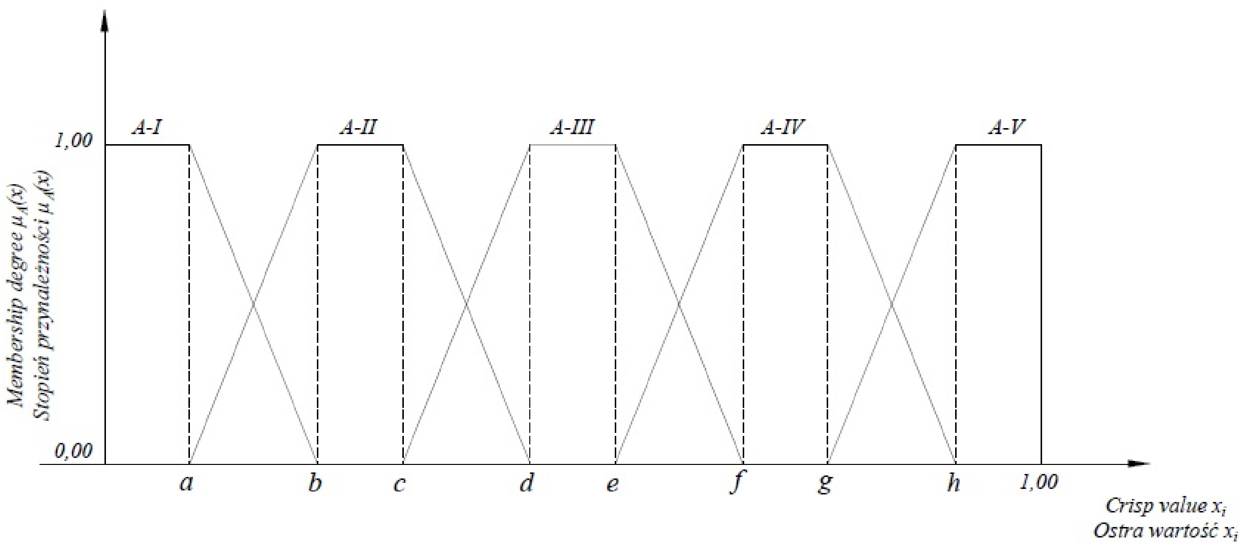

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Fig. 2. Function of belonging of the input set A of the fuzzy model for the method assessing reliability of seasonally operated machines
Rys. 2. Funkcje przynależności zbioru wejściowego A modelu rozmytego metody oceny niezawodności maszyn pracujących sezonowo

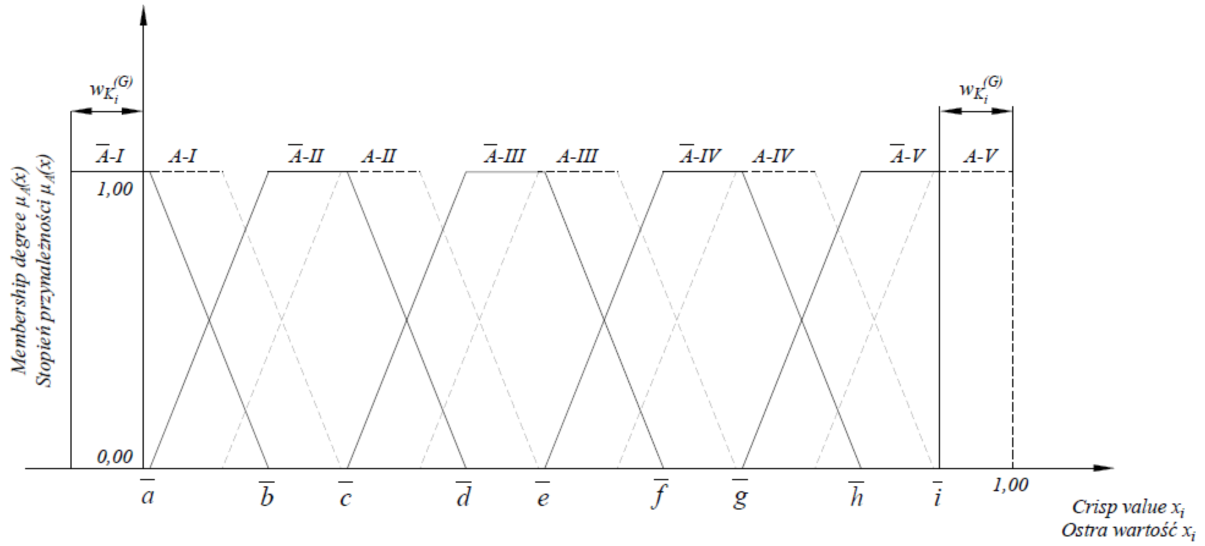

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Fig. 3. Shifted functions belonging to the input set $\overline{A}$ for the method assessing machine reliability

Rys. 3. Przesunięte funkcje przynależności zbioru wejściowego $\overline{A}$ metody oceny niezawodności maszyn

In the fuzzification block vector $\overline{x}$ of inputs is transformed into the vector $\overline{M}$ of the degrees of belonging of these inputs to a fuzzy set, which at the same time becomes an input vector to the block of inference. The block of inference in the method assessing reliability of seasonally operated machines comprises three components: the database of rules, an inference mechanism and the function of belonging for output from the model.

The database of rules, also referred to as the linguistic model, is interpreted as a set cause-and-effect relationships, existing between input sets $\overline{A}$ and output sets B, which continue to be fuzzy sets. The database of rules represents knowledge on typical and possible values of variables of status, which in the method assess reliability of seasonally operated machines. Each rule in the database is composed of part *IF* (antecedent), which is a set of conditions (premises) and from the part *THEN* (consequent) containing a conclusion. The statement on individual rules being met leads to the calculation of the degree of activation of a conclusion of these rules in the form of the function of belonging $\mu_B^{(k)}(y)$. Combining these functions makes it possible to find the resulting function of belonging for the conclusion from the database of rules.

Performance of the fuzzy inference requires first of all an assessment of the degree of meeting (truthfulness) of premises for individual rules. This degree, in contrast to the rules of conventional logic, may assume not only value *0* or *l*, but also fractional values from the interval *<0,1>*. If the degree of satisfying a premise for a given rule is zero, then it is not activated and will not participate in the inference process. The higher the degree of satisfying the premise, the higher the share of a given rule in the determination of the resulting conclusion of the database of rules [2, 6, 7, 8, 17, 19, 20, 21, 29, 36, 37, 38].

The number of rules in the fuzzy model for the method assessing reliability of seasonally operated machines depends on the number of input fuzzy sets $\overline{A}$. The database of rules is characterised by a close relationship with the problem of reliability assessment, completeness (each linguistic status of the input is ascribed at least one linguistic status of the output), consistency (each linguistic status of the input is ascribed at least one linguistic status of the output), consistency (rules may have identical premises, but they must have different conclusions) and continuity (there are no neighbouring rules with sets of conclusions, whose quotient is zero).

The inference mechanism aims at the calculation of the degree of satisfying premises h_i and the degree of activation of conclusions of individual rules $\mu_{B^*}(y_i)$. The operation of determining the degree of meeting premises may be performed using operators *T*- or *S*-standards [19, 20, 21, 31, 36, 37, 38]. In the proposed method assessing reliability of seasonally operated machines, due to the conjunctive character of rules, the minimum operator *(MIN)*, *T*-norm, called the Mandani operator, was used.

The operation to determine the modified function of belonging is performed only for these rules, which premises are met in a degree $h_i>0$ (activated rules); in turn, non-activated rules $(h_i=0)$ do not participate in inference.

Determination of the resulting function of belonging $\mu_{wyn}(y)$ is executed by accumulation of modified functions of belonging $\mu_{B^*}(y_i)$ for conclusions of individual rules, using one of *S*-norms. In the proposed method assessing machine reliability it will be operator *MAX*.

As a result of inference we obtain a resulting function of belonging representing a fuzzy set *B*(y)* of conclusions from the entire database of rules.

The third stage of fuzzy modelling of the method assessing reliability of machines is defuzzification, which comprises the process of reducing a fuzzy set *B*(y)*, constituting output from the inference block to one crip value $\overline{y}$, being at the same time a numerical value of the level of reliability. This value is output from the entire fuzzy model and constitutes a numerical index of reliability I_R for seasonally operated machines.

The output set *B(y)* of the fuzzy model for the method assessing reliability of seasonally operated machines contains 5 terms (Fig. 4). Each of them expresses the level of reliability, which is characterised by linguistic values: set *B-I* – very low level of reliability, set *B-II* – low level of reliability, set *B-II* – medium level of reliability, set *B-IV* - high level of reliability, set *B-V* – very high level of reliability. As it was shown in Fig. 4, the term set *B-I* is plotted by the function of belonging of class *L* (left external function), terms of sets *B-II*, *B-III*, *B-IV*, function of class *Π*, the term set *B-V* is plotted by function *Γ* (right external function).

In the proposed method assessing reliability of seasonally operated machines as a criterion for the selection of a defuzzification method its uniqueness, sensitivity and non-continuity were adopted. Piegat [21] and Zadeh [36] defined sensitivity of defuzzification and thus of the entire fuzzy model as the existence of a reaction of the model output to changes in the degree of activation of fuzzy sets of conclusions from the rules. Non-continuity of defuzzification is defined by the existence of a step-wise reaction of model output to any small change in the degrees of activation of fuzzy sets of conclusions from rules. Uniqueness means that for one fuzzy set only one crip numerical value may be generated.

In the developed method assessing reliability of seasonally operated machines the method of centre of gravity *(COG)* was applied for the crip representative $\overline{y}_{COG}$ of the resulting fuzzy set $B^*(y_i)$, defined by the function of belonging assuming the coordinate y_c of the centre of gravity *C* of area under the curve specific to that function. Values of coordinate y_c may be calculated as a quotient of the moment of area under the curve in relation to axis $\mu_B^*(y_i)$ and the size of that area:

$$\overline{y}_{COG} = y_c = \frac{\int y\mu_{wyn}(y)dy}{\int \mu_{wyn}(y)dy}. \qquad (10)$$

4. Empirical verification of the method assessing reliability

The developed method assessing reliability of seasonally operated machines needs to be verified in terms of the logical accuracy of the proposed algorithm. The logical verification of this method will make it possible to determine its practical applicability and is possible upon meeting the following conditions:

- The investigated group has to include machine users,
- Weights of criteria for assessing reliability have to sum up to one,
- The shape and number of input terms of the function of belonging have to reflect the linguistic scale of assessments of adopted criteria in this method,
- Incorporation of weights of criteria for the assessment of reliability in the fuzzy model results in the shift of input functions of belonging towards the axis of the degrees of belonging, with no change in their shape or the number of terms,
- The database of rules in the block of inference in the fuzzy model has to include all premises and conclusions, resulting from the number of input and output terms of fuzzy sets, while maintaining their logical selection,
- The shape of output functions of belonging and the assumed number of terms reflects the scale of the presented method assessing reliability of seasonally operated machines,
- The adopted method to determine the value of index of I_R depends on the shape of the output function of belonging and its required numerical accuracy,
- The value of I_R has to be within *<0,1>* irrespective of the number of assessments of machine users, the number of adopted criteria and their weight, the shape of input and output functions of belonging, applied inference operators, the defuzzification method in the fuzzy model.

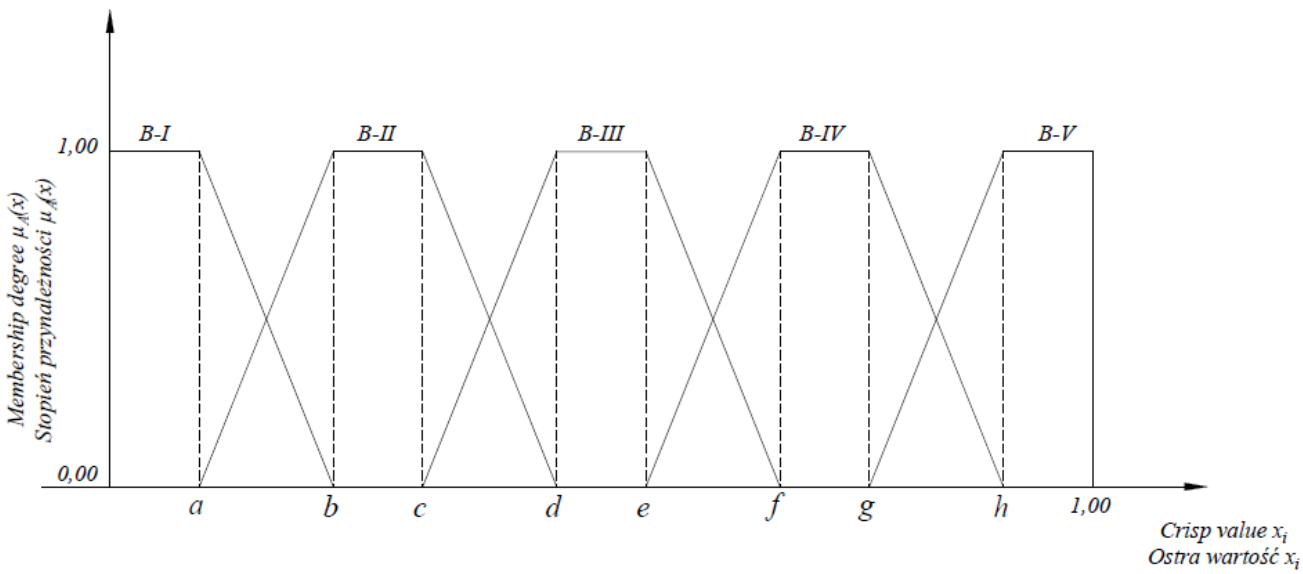

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Fig. 4. Functions of belonging for the output set $B(y_i)$ in the method assessing reliability of seasonally operated machines
Rys. 4. Funkcje przynależności zbioru wyjściowego $B(y_i)$ metody oceny niezawodności maszyn pracujących sezonowo

Verification of the method assessing reliability was performed based on typical seasonally operated machines in agriculture, i.e. cereal combine harvesters. For this purpose a questionnaire survey was conducted, which covered three types of combine harvesters, while the number of combine harvesters for individual types was five. Thus the total number of tested cereal combine harvesters was fifteen. In order to adequately identify the combine harvesters and their users the following notations were applied:

– *A* – type 1 cereal combine harvesters,
– *B* – type 2 cereal combine harvesters,
– *C* – type 3 cereal combine harvesters,
– U_{Ai} – users of type 1 cereal combine harvesters,
– U_{Bi} – users of type 2 cereal combine harvesters,
– U_{Ci} – users of type 3 cereal combine harvesters.

Tab. 1 presents current values of parameters, which characterise the performance of tested cereal combine harvesters.

In analyses of reliability of cereal combine harvesters the following criteria of assessment were adopted:

– length of work period of combine harvester K_1,
– operating conditions of combine harvester K_2,
– storage conditions of combine harvester K_3,
– knowledge and skills of combine harvester operator K_4,
– quality of servicing of combine harvester K_5.

Each users of tested cereal combine harvesters gave a specific score to analysed criteria, which thus resulted in their respective hierarchisation (Tab. 2).

Sign "»" expresses a different hierarchy of importance of assessed criteria, in turn, "=" denotes a lack of such a difference. When analysing the hierarchisation of user U_{A1} ($K_2 = K_5$ » K_1 » $K_3 = K_4$) it was observed that criteria K_2 *and* K_5, and K_3 *and* K_4 are characterised by the same level of importance. However, the level of importance for criteria K_2 *and* K_5 is greater than the level of importance for criteria K_1, K_3 *and* K_4.

Table 1. Performance characteristics of tested cereal combine harvesters
Tab. 1. Charakterystyka eksploatacyjna badanych kombajnów do zbioru zbóż

Performance parameters of combine harvesters	Type of combine harvester		
	A	B	C
Year of production	2009 – 2011	2009 – 2012	2010 – 2013
Number of years in use (-)	5 – 7	4 – 7	3 – 6
Number of engine work hours (h)	1600 – 2200	1550 – 2200	950 – 1600
Number of work hours for threshing aggregate (h)	1120 – 1600	1050 – 1400	860 – 1300

Source: own work / Źródło: opracowanie własne

Table 2. Point score quantification of criteria in assessment of reliability of cereal combine harvesters
Tab. 2. Punktowa kwantyfikacja kryteriów oceny niezawodności kombajnów do zbioru zbóż

User machines / Criteriaa [K_i]	U_{A1}	U_{A2}	U_{A3}	U_{A4}	U_{A5}	U_{B1}	U_{B2}	U_{B3}	U_{B4}	U_{B5}	U_{C1}	U_{C2}	U_{C3}	U_{C4}	U_{C5}
K_1	20	25	10	15	10	5	15	15	25	10	10	15	20	10	20
K_2	25	20	25	25	30	25	25	20	10	30	25	15	25	25	20
K_3	15	25	25	25	10	10	10	20	10	10	10	20	25	10	15
K_4	15	20	25	20	25	20	25	20	25	25	25	25	20	20	15
K_5	25	10	15	15	25	40	25	25	30	25	25	25	10	35	30
Sum	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100

Source: own work / Źródło: opracowanie własne

Table 3. Hierarchisation of criteria in the assessment of reliability of cereal combine harvesters
Tab. 3. Hierarchizacja kryteriów oceny niezawodności kombajnów do zbioru zbóż

Machine user	Hierarchy of criteria
U_{A1}	$K_2 = K_5$ » K_1 » $K_3 = K_4$
U_{A2}	$K_1 = K_3$ » $K_2 = K_4$ » K_5
U_{A3}	$K_2 = K_3 = K_4$ » K_5 » K_1
U_{A4}	$K_2 = K_3$ » K_4 » $K_1 = K_5$
U_{A5}	$K_2 = K_4 = K_5$ » $K_1 = K_3$
U_{B1}	K_5 » K_2 » K_4 » K_3 » K_1
U_{B2}	$K_2 = K_4 = K_5$ » K_1 » K_3
U_{B3}	K_5 » $K_2 = K_3 = K_4$ » K_1
U_{B4}	K_5 » $K_1 = K_4$ » $K_2 = K_3$
U_{B5}	K_2 » $K_4 = K_5$ » $K_1 = K_3$
U_{C1}	$K_2 = K_4 = K_5$ » $K_1 = K_3$
U_{C2}	$K_4 = K_5$ » K_3 » $K_1 = K_2$
U_{C3}	$K_2 = K_3$ » $K_1 = K_4$ » K_5
U_{C4}	K_5 » K_2 » K_4 » $K_1 = K_3$
U_{C5}	K_5 » $K_1 = K_2$ » $K_3 = K_4$

Source: own work / Źródło: opracowanie własne

Tab. 4 presents results of calculations for the matrix of pair-wise comparisons, a conditional matrix and partial weights of all criteria adopted in the assessment of reliability of cereal combine harvesters. When analysing further the assessment of user $U_{A1\ may}$ we may see that criteria K_2, K_5 have a weight of 0.36. Criterion K_1 has a weight of 0.15, while criteria K_3, K_4 0.06, which is consistent with the expression $K_2 = K_5$ » K_1 » $K_3 = K_4$.

Table 4. Results of calculations for the matrix of pair-wise comparisons, the normalised matrix and weights of criteria in the assessment of reliability of cereal combine harvesters

Tab. 4. Wyniki obliczeń macierzy porównań parami, macierzy unormowanej oraz wag kryteriów oceny niezawodności kombajnów do zbioru zbóż

$A^{(0)}$	Matrix of pair-wise comparisons $K^{(0)}_{5-5}$					conditional matrix of pair-wise comparisons $\overline{K}^{(0)}_{5-5}$					Total	Weight $[w_{U_i,K_i}]$
Criteria $[K_i]$	K_1	K_2	K_3	K_4	K_5	K_1	K_2	K_3	K_4	K_5		
U_{A1}												
K_1	1.00	0.33	3.00	3.00	0.33	0.13	0.12	0.20	0.20	0.12	0.77	0.15
K_2	3.00	1.00	5.00	5.00	1.00	0.39	0.37	0.33	0.33	0.37	1.79	0.36
K_3	0.33	0.20	1.00	1.00	0.20	0.04	0.07	0.07	0.07	0.07	0.32	0.06
K_4	0.33	0.20	1.00	1.00	0.20	0.04	0.07	0.07	0.07	0.07	0.32	0.06
K_5	3.00	1.00	5.00	5.00	1.00	0.39	0.37	0.33	0.33	0.37	1.79	0.36
∑	7.66	2.73	15.00	15.00	2.73	1.00	1.00	1.00	1.00	1.00	5.00	1.00
U_{A2}												
K_1	1.00	3.00	1.00	3.00	5.00	0.35	0.36	0.35	0.36	0.29	1.71	0.34
K_2	0.33	1.00	0.33	1.00	3.00	0.12	0.12	0.12	0.12	0.18	0.65	0.13
K_3	1.00	3.00	1.00	3.00	5.00	0.35	0.36	0.35	0.36	0.29	1.71	0.34
K_4	0.33	1.00	0.33	1.00	3.00	0.12	0.12	0.12	0.12	0.18	0.65	0.13
K_5	0.20	0.33	0.20	0.33	1.00	0.07	0.04	0.07	0.04	0.06	0.28	0.06
∑	2.86	8.33	2.86	8.33	17.00	1.00	1.00	1.00	1.00	1.00	5.00	1.00
U_{A3}												
K_1	1.00	0.20	0.20	0.20	0.33	0.05	0.06	0.06	0.06	0.03	0.25	0.05
K_2	5.00	1.00	1.00	1.00	3.00	0.26	0.28	0.28	0.28	0.29	1.40	0.28
K_3	5.00	1.00	1.00	1.00	3.00	0.26	0.28	0.28	0.28	0.29	1.40	0.28
K_4	5.00	1.00	1.00	1.00	3.00	0.26	0.28	0.28	0.28	0.29	1.40	0.28
K_5	3.00	0.33	0.33	0.33	1.00	0.16	0.09	0.09	0.09	0.10	0.54	0.11
∑	19.00	3.53	3.53	3.53	10.33	1.00	1.00	1.00	1.00	1.00	5.00	1.00
U_{A4}												
K_1	1.00	0.20	0.20	0.33	1.00	0.07	0.07	0.07	0.04	0.07	0.32	0.06
K_2	5.00	1.00	1.00	3.00	5.00	0.33	0.37	0.37	0.39	0.33	1.79	0.36
K_3	5.00	1.00	1.00	3.00	5.00	0.33	0.37	0.37	0.39	0.33	1.79	0.36
K_4	3.00	0.33	0.33	1.00	3.00	0.20	0.12	0.12	0.13	0.20	0.77	0.15
K_5	1.00	0.20	0.20	0.33	1.00	0.07	0.07	0.07	0.04	0.07	0.32	0.06
∑	15.00	2.73	2.73	7.66	15.00	1.00	1.00	1.00	1.00	1.00	5.00	1.00
U_{A5}												
K_1	1.00	0.33	1.00	0.33	0.33	0.09	0.09	0.09	0.11	0.06	0.44	0.09
K_2	3.00	1.00	3.00	1.00	1.00	0.27	0.27	0.27	0.33	0.18	1.33	0.27
K_3	1.00	0.33	1.00	0.33	0.33	0.09	0.09	0.09	0.11	0.06	0.44	0.09
K_4	3.00	1.00	3.00	1.00	3.00	0.27	0.27	0.27	0.33	0.53	1.68	0.34
K_5	3.00	1.00	3.00	0.33	1.00	0.27	0.27	0.27	0.11	0.18	1.11	0.22
∑	11.00	3.66	11.00	2.99	5.66	1.00	1.00	1.00	1.00	1.00	5.00	1.00
U_{B1}												
K_1	1.00	0.14	0.33	0.20	0.11	0.04	0.03	0.02	0.02	0.06	0.17	0.03
K_2	7.00	1.00	5.00	3.00	0.33	0.28	0.21	0.31	0.31	0.19	1.30	0.26
K_3	3.00	0.20	1.00	0.33	0.14	0.12	0.04	0.06	0.03	0.08	0.34	0.07
K_4	5.00	0.33	3.00	1.00	0.20	0.20	0.07	0.18	0.10	0.11	0.67	0.13
K_5	9.00	3.00	7.00	5.00	1.00	0.36	0.64	0.43	0.52	0.56	2.52	0.50
∑	25.00	4.67	16.33	9.53	1.78	1.00	1.00	1.00	1.00	1.00	5.00	1.00
U_{B2}												
K_1	1.00	0.33	3.00	0.33	0.33	0.10	0.09	0.16	0.09	0.09	0.54	0.11
K_2	3.00	1.00	5.00	1.00	1.00	0.29	0.28	0.26	0.28	0.28	1.40	0.28
K_3	0.33	0.20	1.00	0.20	0.20	0.03	0.06	0.05	0.06	0.06	0.25	0.05
K_4	3.00	1.00	5.00	1.00	1.00	0.29	0.28	0.26	0.28	0.28	1.40	0.28
K_5	3.00	1.00	5.00	1.00	1.00	0.29	0.28	0.26	0.28	0.28	1.40	0.28
∑	10.33	3.53	19.00	3.53	3.53	1.00	1.00	1.00	1.00	1.00	5.00	1.00
U_{B3}												
K_1	1.00	0.33	0.33	0.33	0.20	0.07	0.05	0.05	0.05	0.09	0.31	0.06
K_2	3.00	1.00	1.00	1.00	0.33	0.20	0.16	0.16	0.16	0.15	0.82	0.16
K_3	3.00	1.00	1.00	1.00	0.33	0.20	0.16	0.16	0.16	0.15	0.82	0.16

cont. of the Table 4 / cd tab. 4

K_4	3.00	1.00	1.00	1.00	0.33	0.20	0.16	0.16	0.16	0.15	0.82	0.16
K_5	5.00	3.00	3.00	3.00	1.00	0.33	0.47	0.47	0.47	0.46	2.21	0.44
∑	15.00	6.33	6.33	6.33	2.19	1.00	1.00	1.00	1.00	1.00	5.00	1.00
U_{B4}												
K_1	1.00	3.00	3.00	1.00	0.33	0.18	0.23	0.23	0.18	0.16	0.98	0.20
K_2	0.33	1.00	1.00	0.33	0.20	0.06	0.08	0.08	0.06	0.10	0.37	0.07
K_3	0.33	1.00	1.00	0.33	0.20	0.06	0.08	0.08	0.06	0.10	0.37	0.07
K_4	1.00	3.00	3.00	1.00	0.33	0.18	0.23	0.23	0.18	0.16	0.98	0.20
K_5	3.00	5.00	5.00	3.00	1.00	0.53	0.38	0.38	0.53	0.49	2.31	0.46
∑	5.66	13.00	13.00	5.66	2.06	1.00	1.00	1.00	1.00	1.00	5.00	1.00
U_{B5}												
K_1	1.00	0.20	1.00	0.33	0.33	0.08	0.02	0.11	0.11	0.11	0.43	0.09
K_2	5.00	1.00	1.00	0.33	0.33	0.38	0.12	0.11	0.11	0.11	0.84	0.17
K_3	1.00	1.00	1.00	0.33	0.33	0.08	0.12	0.11	0.11	0.11	0.53	0.11
K_4	3.00	3.00	3.00	1.00	1.00	0.23	0.37	0.33	0.33	0.33	1.60	0.32
K_5	3.00	3.00	3.00	1.00	1.00	0.23	0.37	0.33	0.33	0.33	1.60	0.32
∑	13.00	8.20	9.00	2.99	2.99	1.00	1.00	1.00	1.00	1.00	5.00	1.00
U_{C1}												
K_1	1.00	0.33	1.00	0.33	0.33	0.09	0.04	0.09	0.09	0.09	0.40	0.08
K_2	3.00	1.00	3.00	1.00	1.00	0.27	0.12	0.27	0.27	0.27	1.21	0.24
K_3	1.00	1.00	1.00	0.33	0.33	0.09	0.12	0.09	0.09	0.09	0.48	0.10
K_4	3.00	3.00	3.00	1.00	1.00	0.27	0.36	0.27	0.27	0.27	1.45	0.29
K_5	3.00	3.00	3.00	1.00	1.00	0.27	0.36	0.27	0.27	0.27	1.45	0.29
∑	11.00	8.33	11.00	3.66	3.66	1.00	1.00	1.00	1.00	1.00	5.00	1.00
U_{C2}												
K_1	1.00	1.00	0.33	0.20	0.20	0.07	0.07	0.04	0.07	0.07	0.32	0.06
K_2	1.00	1.00	0.33	0.20	0.20	0.07	0.07	0.04	0.07	0.07	0.32	0.06
K_3	3.00	3.00	1.00	0.33	0.33	0.20	0.20	0.13	0.12	0.12	0.77	0.15
K_4	5.00	5.00	3.00	1.00	1.00	0.33	0.33	0.39	0.37	0.37	1.79	0.36
K_5	5.00	5.00	3.00	1.00	1.00	0.33	0.33	0.39	0.37	0.37	1.79	0.36
∑	15.00	15.00	7.66	2.73	2.73	1.00	1.00	1.00	1.00	1.00	5.00	1.00
U_{C3}												
K_1	1.00	0.33	0.33	1.00	3.00	0.12	0.12	0.12	0.12	0.18	0.65	0.13
K_2	3.00	1.00	1.00	3.00	5.00	0.36	0.35	0.35	0.36	0.29	1.71	0.34
K_3	3.00	1.00	1.00	3.00	5.00	0.36	0.35	0.35	0.36	0.29	1.71	0.34
K_4	1.00	0.33	0.33	1.00	3.00	0.12	0.12	0.12	0.12	0.18	0.65	0.13
K_5	0.33	0.20	0.20	0.33	1.00	0.04	0.07	0.07	0.04	0.06	0.28	0.06
∑	8.33	2.86	2.86	8.33	17.00	1.00	1.00	1.00	1.00	1.00	5.00	1.00
U_{C4}												
K_1	1.00	0.20	1.00	0.33	0.14	0.06	0.04	0.06	0.03	0.08	0.27	0.05
K_2	5.00	1.00	5.00	3.00	0.33	0.29	0.21	0.29	0.31	0.18	1.29	0.26
K_3	1.00	0.20	1.00	0.33	0.14	0.06	0.04	0.06	0.03	0.08	0.27	0.05
K_4	3.00	0.33	3.00	1.00	0.20	0.18	0.07	0.18	0.10	0.11	0.64	0.13
K_5	7.00	3.00	7.00	5.00	1.00	0.41	0.63	0.41	0.52	0.55	2.53	0.51
∑	17.00	4.73	17.00	9.66	1.81	1.00	1.00	1.00	1.00	1.00	5.00	1.00
U_{C5}												
K_1	1.00	1.00	3.00	3.00	0.33	0.18	0.18	0.23	0.23	0.16	0.98	0.20
K_2	1.00	1.00	3.00	3.00	0.33	0.18	0.18	0.23	0.23	0.16	0.98	0.20
K_3	0.33	0.33	1.00	1.00	0.20	0.06	0.06	0.08	0.08	0.10	0.37	0.07
K_4	0.33	0.33	1.00	1.00	0.20	0.06	0.06	0.08	0.08	0.10	0.37	0.07
K_5	3.00	3.00	5.00	5.00	1.00	0.53	0.53	0.38	0.38	0.49	2.31	0.46
∑	5.66	5.66	13.00	13.00	2.06	1.00	1.00	1.00	1.00	1.00	5.00	1.00

Source: own work / Źródło: opracowanie własne

As a result of the calculations each criterion has as many different weights, as many machine users expressed their opinions. Using equation (8), sums of partial weights were calculated and next the obtained results were divided by the number of respondents. In this way global weights $w_{K_i}^{(G)}$ were established for the criterion of reliability assessment (Tab. 5).

Table 5. Values of global weights for main criteria $w_{K_i}^{(G)}$ representative for group of participating users of combine harvesters

Tab. 5. Wartości globalnych wag kryteriów głównych $w_{K_i}^{(G)}$ reprezentatywne dla grupy badanych użytkowników kombajnów

Weight of main criterion $w_{K_i}^{(G)}$				
K_1	K_2	K_3	K_4	K_5
0.11	0.23	0.15	0.20	0.30

Source: own work / Źródło: opracowanie własne

Among the criteria the greatest weight ($w^{(G)}_{K_i}$ = 0.30) was found for the criterion of quality of servicing for cereal combine harvesters. The lowest weight ($w^{(G)}_{K_i}$ = 0.11) was obtained for the criterion of the length of work period of tested combine harvesters.

Global weights for main criteria constitute the output in construction of the fuzzy model for the method assessing reliability of seasonally operated machines. Calculated values make it possible to determine the shift of the function of belonging towards axis $\mu_{A_i}(x_i)$.

The shift in graphs for the input functions in the fuzzy model for the method assessing reliability of seasonally operated machines results in the inclusion of greater values of the degrees of belonging for criteria of greater value for the population of users of tested combine harvesters.

Due to the large number of combinations of rules, the database contains the most characteristic premises and conclusions. In turn, extreme rules are rejected, in which at the lowest scores for criteria quantification of reliability of seasonally operated machines is high or very high, which was expressed as:

$$
\begin{aligned}
&r^{(1)}:\left(\overline{x}_I \text{ is } \overline{A}-I \text{ AND } \overline{x}_{II} \text{ is } \overline{A}-I \text{ AND } \overline{x}_{III} \text{ is } \overline{A}-I \text{ AND } \overline{x}_{IV} \text{ is } \overline{A}-I \text{ AND } \overline{x}_V \text{ is } \overline{A}-I\right) \text{THEN } (y_1 \text{ is } B-I)\\
&r^{(2)}:\left(\overline{x}_I \text{ is } \overline{A}-II \text{ AND } \overline{x}_{II} \text{ is } \overline{A}-I \text{ AND } \overline{x}_{III} \text{ is } \overline{A}-I \text{ AND } \overline{x}_{IV} \text{ is } \overline{A}-I \text{ AND } \overline{x}_V \text{ is } \overline{A}-I\right) \text{THEN } (y_2 \text{ is } B-I)\\
&r^{(3)}:\left(\overline{x}_I \text{ is } \overline{A}-III \text{ AND } \overline{x}_{II} \text{ is } \overline{A}-I \text{ AND } \overline{x}_{III} \text{ is } \overline{A}-I \text{ AND } \overline{x}_{IV} \text{ is } \overline{A}-I \text{ AND } \overline{x}_V \text{ is } \overline{A}-I\right) \text{THEN } (y_3 \text{ is } B-I)\\
&r^{(4)}:\left(\overline{x}_I \text{ is } \overline{A}-IV \text{ AND } \overline{x}_{II} \text{ is } \overline{A}-I \text{ AND } \overline{x}_{III} \text{ is } \overline{A}-I \text{ AND } \overline{x}_{IV} \text{ is } \overline{A}-I \text{ AND } \overline{x}_V \text{ is } \overline{A}-I\right) \text{THEN } (y_4 \text{ is } B-II)\\
&r^{(5)}:\left(\overline{x}_I \text{ is } \overline{A}-V \text{ AND } \overline{x}_{II} \cdots \text{is } \overline{A}-I \text{ AND } \overline{x}_{III} \text{ is } \overline{A}-I \text{ AND } \overline{x}_{IV} \text{ is } \overline{A}-I \text{ AND } \overline{x}_V \text{ is } \overline{A}-I\right) \text{THEN } (y_5 \text{ is } B-II)\\
&r^{(6)}:\left(\overline{x}_I \text{ is } \overline{A}-I \text{ AND } \overline{x}_{II} \text{ is } \overline{A}-II \text{ AND } \overline{x}_{III} \text{ is } \overline{A}-I \text{ AND } \overline{x}_{IV} \text{ is } \overline{A}-I \text{ AND } \overline{x}_V \text{ is } \overline{A}-I\right) \text{THEN } (y_6 \text{ is } B-I)\\
&r^{(7)}:\left(\overline{x}_I \text{ is } \overline{A}-I \text{ AND } \overline{x}_{II} \text{ is } \overline{A}-III \text{ AND } \overline{x}_{III} \text{ is } \overline{A}-I \text{ AND } \overline{x}_{IV} \text{ is } \overline{A}-I \text{ AND } \overline{x}_V \text{ is } \overline{A}-I\right) \text{THEN } (y_7 \text{ is } B-I)\\
&r^{(8)}:\left(\overline{x}_I \text{ is } \overline{A}-I \text{ AND } \overline{x}_{II} \text{ is } \overline{A}-IV \text{ AND } \overline{x}_{III} \text{ is } \overline{A}-I \text{ AND } \overline{x}_{IV} \text{ is } \overline{A}-I \text{ AND } \overline{x}_V \text{ is } \overline{A}-I\right) \text{THEN } (y_8 \text{ is } B-II)\\
&r^{(9)}:\left(\overline{x}_I \text{ is } \overline{A}-I \text{ AND } \overline{x}_{II} \text{ is } \overline{A}-V \text{ AND} \ldots \overline{x}_{III} \text{ is } \overline{A}-I \text{ AND } \overline{x}_{IV} \text{ is } \overline{A}-I \text{ AND } \overline{x}_V \text{ is } \overline{A}-I\right) \text{THEN } (y_9 \text{ is } B-II)\\
&r^{(10)}:\left(\overline{x}_I \text{ is } \overline{A}-I \text{ AND } \overline{x}_{II} \text{ is } \overline{A}-I \text{ AND } \overline{x}_{III} \text{ is } \overline{A}-II \text{ AND } \overline{x}_{IV} \text{ is } \overline{A}-I \text{ AND } \overline{x}_V \text{ is } \overline{A}-I\right) \text{THEN } (y_{10} \text{ is } B-I) \qquad \vdots\\
&r^{(593775)}:\left(\overline{x}_I \text{ is } \overline{A}-V \text{ AND } \overline{x}_{II} \text{ is } \overline{A}-V \text{ AND } \overline{x}_{III} \text{ is } \overline{A}-V \text{ AND } \overline{x}_{IV} \text{ is } \overline{A}-V \text{ AND } \overline{x}_V \text{ is } \overline{A}-V\right) \text{THEN } (y_{593775} \text{ is } B-V) \qquad (20)
\end{aligned}
$$

The next stage in the quantification of reliability of cereal combine harvesters consists in their point score assessment based on the adopted criteria. The scale of scores is determined by the number of input terms in the fuzzy sets for individual criteria of assessment. For five terms a 5-point scale is used, with 5.00 denoting the best assessment, while 1.00 the worst. The quotient of the sum of scores and their maximum number makes it possible to determine crip numerical values for input values of the model and to determine their degrees of belonging to fuzzy sets (Tab. 6).

Results of the inference mechanism $\mu_{B*}(y_i)$, which aims at the calculation of the degree of activation for conclusions from individual rules and determination of the resulting function of belonging $\mu_{wyn}(y)$, are presented in Tab. 7.

Table 6. A list of point-score assessment of reliability of seasonally operated machines according to adopted criteria
Tab. 6. Zestawienie punktowej oceny niezawodności maszyn pracujących sezonowo według przyjętych kryteriów

Criteriaa *[Ki]* / Users of machines *[Ui]*	K_1		K_2		K_3		K_4		K_5	
Combine harvesters type *A*										
U_{A1}	3.00		4.00		3.00		3.00		3.00	
U_{A2}	2.00		3.00		1.00		2.00		3.00	
U_{A3}	4.00		4.00		3.00		4.00		4.00	
U_{A4}	3.00		2.00		1.00		1.00		2.00	
U_{A5}	3.00		4.00		3.00		2.00		1.00	
total	15.00		17.00		11.00		12.00		13.00	
crip value of function of belonging *[xi]*	0.60		0.68		0.44		0.48		0.52	
Terms of fuzzy sets	$\overline{A}-IV$	---	---	$\overline{A}-V$	$\overline{A}-III$	$\overline{A}-IV$	---	$\overline{A}-IV$	$\overline{A}-IV$	$\overline{A}-V$
Degrees of belonging for crip inputs to a fuzzy set $\mu_{\overline{A}_i}(\overline{x}_i)$	1.00	0.00	0.00	1.00	0.32	0.68	0.00	1.00	0.65	0.35
Combine harvesters type *B*										
U_{B1}	4.00		4.00		3.00		3.00		3.00	
U_{B2}	2.00		3.00		1.00		2.00		3.00	
U_{B3}	4.00		4.00		2.00		3.00		3.00	
U_{B4}	3.00		2.00		1.00		1.00		3.00	
U_{B5}	3.00		3.00		2.00		2.00		1.00	
Sum	16.00		16.00		9.00		11.00		13.00	
crip value of function of belonging *[xi]*	0.64		0.64		0.36		0.44		0.52	
Terms of fuzzy sets	$\overline{A}-IV$	---	$\overline{A}-IV$	$\overline{A}-V$	$\overline{A}-III$	---	$\overline{A}-III$	$\overline{A}-IV$	$\overline{A}-IV$	$\overline{A}-V$

cont. of the Table 6 / cd tab. 6

Degrees of belonging for crip inputs to a fuzzy set $\mu_{\bar{A}_i}(\bar{x}_i)$	1.00	0.00	0.29	0.71	1.00	0.00	0.31	0.69	0.65	0.35
Combine harvesters type *C*										
U_{C1}	4.00		2.00		1.00		1.00		4.00	
U_{C2}	3.00		4.00		4.00		2.00		2.00	
U_{C3}	3.00		3.00		3.00		4.00		3.00	
U_{C4}	2.00		3.00		3.00		3.00		3.00	
U_{C5}	3.00		4.00		2.00		4.00		1.00	
Sum	15.00		16.00		13.00		14.00		13.00	
crip value of function of belonging *[x_i]*	0.60		0.64		0.52		0.56		0.52	
Terms of fuzzy sets	$\bar{A}-IV$	---	$\bar{A}-IV$	$\bar{A}-V$	$\bar{A}-III$	$\bar{A}-IV$	---	$\bar{A}-IV$	$\bar{A}-IV$	$\bar{A}-V$
Degrees of belonging for crip inputs to a fuzzy set $\mu_{\bar{A}_i}(\bar{x}_i)$	1.00	0.00	0.29	0.71	0.09	0.91	0.00	1.00	0.65	0.35

Source: own work / Źródło: opracowanie własne

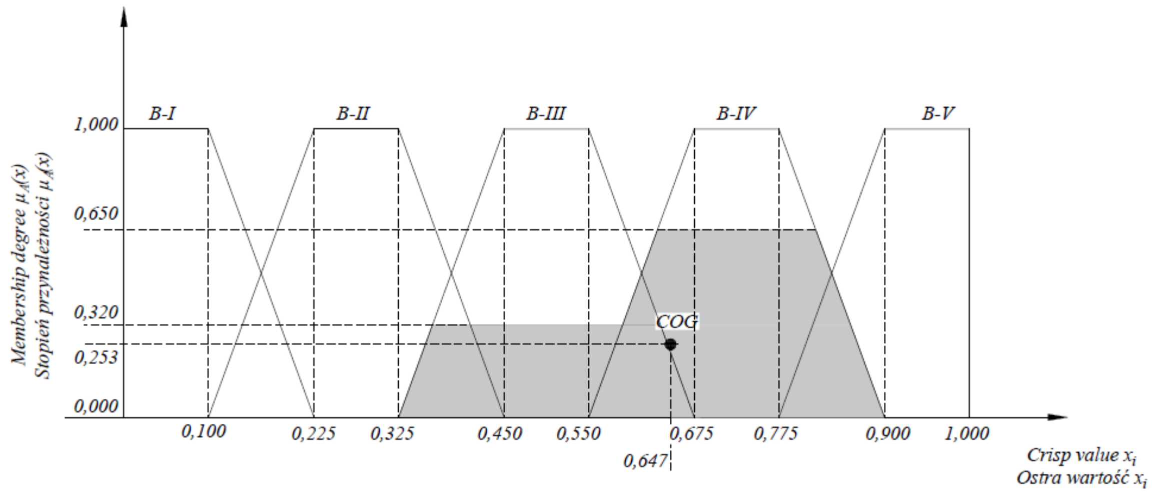
Table 7. Values of modified function of belonging for assessment of reliability of cereal combine harvesters
Tab. 7. Wartości zmodyfikowanej funkcji przynależności oceny niezawodności kombajnów do zbioru zbóż

$r^{(i)}$	*Activated rules*	*Value of modified function of belonging* $\mu_{B*}(y_i)$
Combine harvesters A		
$r^{(A100)}$	$(\bar{x}_I\ is\ \bar{A}-IV\ AND\ \bar{x}_{II}\ is\ \bar{A}-V\ AND\ \bar{x}_{III}\ is\ \bar{A}-III\ AND\ \bar{x}_{IV}\ is\ \bar{A}-IV\ AND\ \bar{x}_V\ is\ \bar{A}-IV)\ THEN\ (y_1\ is\ B-III)$	*0,32*
$r^{(A101)}$	$(\bar{x}_I\ is\ \bar{A}-IV\ AND\ \bar{x}_{II}\ is\ \bar{A}-V\ AND\ \bar{x}_{III}\ is\ \bar{A}-IV\ AND\ \bar{x}_{IV}\ is\ \bar{A}-IV\ AND\ \bar{x}_V\ is\ \bar{A}-IV)\ THEN\ (y_1\ is\ B-IV)$	*0,65*
$r^{(A102)}$	$(\bar{x}_I\ is\ \bar{A}-IV\ AND\ \bar{x}_{II}\ is\ \bar{A}-V\ AND\ \bar{x}_{III}\ is\ \bar{A}-III\ AND\ \bar{x}_{IV}\ is\ \bar{A}-IV\ AND\ \bar{x}_V\ is\ \bar{A}-V)\ THEN\ (y_1\ is\ B-IV)$	*0,32*
$r^{(A103)}$	$(\bar{x}_I\ is\ \bar{A}-IV\ AND\ \bar{x}_{II}\ is\ \bar{A}-V\ AND\ \bar{x}_{III}\ is\ \bar{A}-IV\ AND\ \bar{x}_{IV}\ is\ \bar{A}-IV\ AND\ \bar{x}_V\ is\ \bar{A}-V)\ THEN\ (y_1\ is\ B-IV)$	*0,35*
Resulting function of belonging		
	$\mu_{wyn}(y_A)$	*0,65*
Combine harvesters B		
$r^{(B100)}$	$(\bar{x}_I\ is\ \bar{A}-IV\ AND\ \bar{x}_{II}\ is\ \bar{A}-IV\ AND\ \bar{x}_{III}\ is\ \bar{A}-III\ AND\ \bar{x}_{IV}\ is\ \bar{A}-III\ AND\ \bar{x}_V\ is\ \bar{A}-IV)\ THEN\ (y_1\ is\ B-III)$	*0,29*
$r^{(B101)}$	$(\bar{x}_I\ is\ \bar{A}-IV\ AND\ \bar{x}_{II}\ is\ \bar{A}-IV\ AND\ \bar{x}_{III}\ is\ \bar{A}-III\ AND\ \bar{x}_{IV}\ is\ \bar{A}-IV\ AND\ \bar{x}_V\ is\ \bar{A}-IV)\ THEN\ (y_1\ is\ B-IV)$	*0,29*
$r^{(B102)}$	$(\bar{x}_I\ is\ \bar{A}-IV\ AND\ \bar{x}_{II}\ is\ \bar{A}-IV\ AND\ \bar{x}_{III}\ is\ \bar{A}-III\ AND\ \bar{x}_{IV}\ is\ \bar{A}-III\ AND\ \bar{x}_V\ is\ \bar{A}-V)\ THEN\ (y_1\ is\ B-IV)$	*0,29*
$r^{(B103)}$	$(\bar{x}_I\ is\ \bar{A}-IV\ AND\ \bar{x}_{II}\ is\ \bar{A}-V\ AND\ \bar{x}_{III}\ is\ \bar{A}-III\ AND\ \bar{x}_{IV}\ is\ \bar{A}-III\ AND\ \bar{x}_V\ is\ \bar{A}-V)\ THEN\ (y_1\ is\ B-IV)$	*0,31*
…	…	…
$r^{(B120)}$	$(\bar{x}_I\ is\ \bar{A}-IV\ AND\ \bar{x}_{II}\ is\ \bar{A}-V\ AND\ \bar{x}_{III}\ is\ \bar{A}-III\ AND\ \bar{x}_{IV}\ is\ \bar{A}-IV\ AND\ \bar{x}_V\ is\ \bar{A}-IV)\ THEN\ (y_1\ is\ B-IV)$	*0,65*
Resulting function of belonging		
	$\mu_{wyn}(y_B)$	*0,65*
Combine harvesters C		
$r^{(C100)}$	$(\bar{x}_I\ is\ \bar{A}-IV\ AND\ \bar{x}_{II}\ is\ \bar{A}-IV\ AND\ \bar{x}_{III}\ is\ \bar{A}-III\ AND\ \bar{x}_{IV}\ is\ \bar{A}-IV\ AND\ \bar{x}_V\ is\ \bar{A}-IV)\ THEN\ (y_1\ is\ B-IV)$	*0,09*
$r^{(C101)}$	$(\bar{x}_I\ is\ \bar{A}-IV\ AND\ \bar{x}_{II}\ is\ \bar{A}-IV\ AND\ \bar{x}_{III}\ is\ \bar{A}-IV\ AND\ \bar{x}_{IV}\ is\ \bar{A}-IV\ AND\ \bar{x}_V\ is\ \bar{A}-IV)\ THEN\ (y_1\ is\ B-IV)$	*0,29*
$r^{(C102)}$	$(\bar{x}_I\ is\ \bar{A}-IV\ AND\ \bar{x}_{II}\ is\ \bar{A}-IV\ AND\ \bar{x}_{III}\ is\ \bar{A}-IV\ AND\ \bar{x}_{IV}\ is\ \bar{A}-IV\ AND\ \bar{x}_V\ is\ \bar{A}-V)\ THEN\ (y_1\ is\ B-IV)$	*0,29*
$r^{(C103)}$	$(\bar{x}_I\ is\ \bar{A}-IV\ AND\ \bar{x}_{II}\ is\ \bar{A}-IV\ AND\ \bar{x}_{III}\ is\ \bar{A}-III\ AND\ \bar{x}_{IV}\ is\ \bar{A}-IV\ AND\ \bar{x}_V\ is\ \bar{A}-V)\ THEN\ (y_1\ is\ B-IV)$	*0,09*
…		
$r^{(C120)}$	$(\bar{x}_I\ is\ \bar{A}-IV\ AND\ \bar{x}_{II}\ is\ \bar{A}-V\ AND\ \bar{x}_{III}\ is\ \bar{A}-IV\ AND\ \bar{x}_{IV}\ is\ \bar{A}-IV\ AND\ \bar{x}_V\ is\ \bar{A}-IV)\ THEN\ (y_1\ is\ B-IV)$	*0,65*
Resulting function of belonging		
	$\mu_{wyn}(y_C)$	*0,65*

Source: own work / Źródło: opracowanie własne

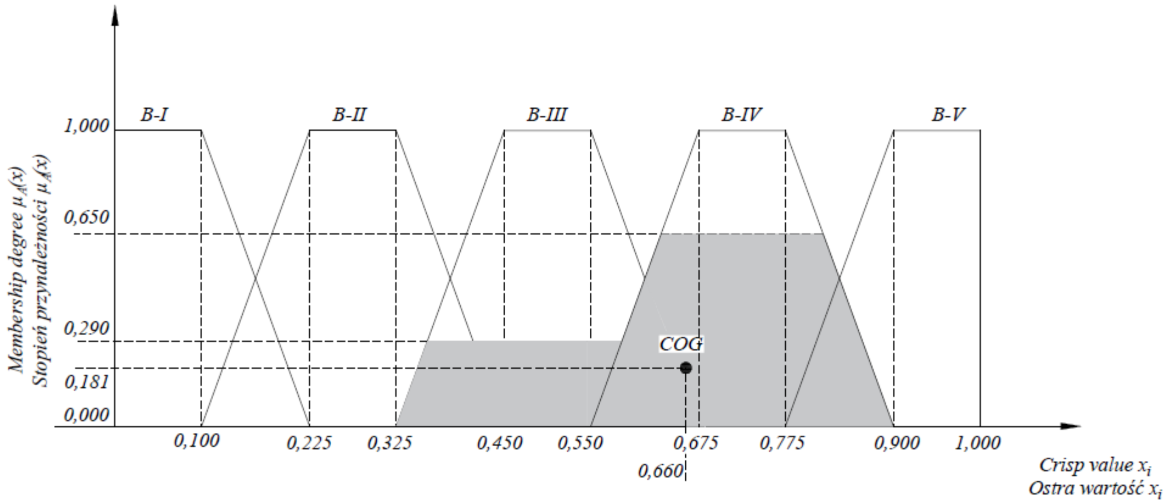
In the third stage of verification of the fuzzy model for the method assessing reliability of machines defuzzification was performed. It consisted in the accumulation of conclusions and reducing the fuzzy set *B*(y)*, constituting the output from the block of inference to one crip numerical value $\bar{y}$, which at the same time is the numerical value of the level of reliability I_R.

For the analysed cereal combine harvesters the index of reliability I_R is presented in Figs. 5-7. Obtained results were referred to the adopted linguistic scale, which makes it possible to assess the level of reliability of combine harvesters as high. The lowest value of I_R was found for combine harvesters type *A* (0.647); in turn, the highest - combine harvesters type *C* (0.725). For combine harvesters type B the value of the index of reliability is $I_R = B$ of 0.660.



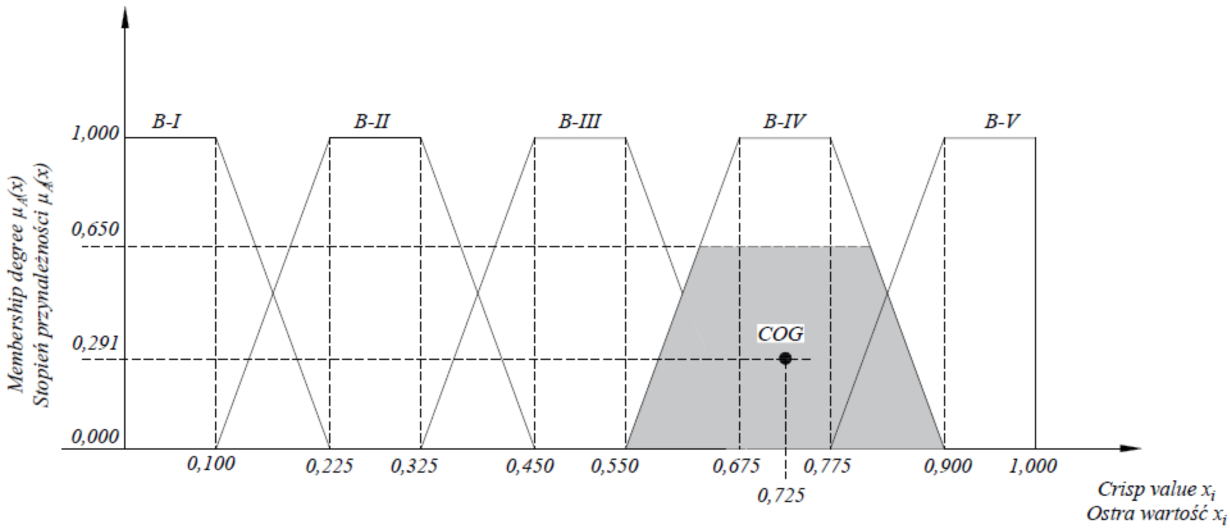
Source: own work / Źródło: opracowanie własne

Fig. 5. Accumulated functions of belonging for the output set *B*(y)* in the assessment of reliability of combine harvester *A*
Rys. 5. Akumulacyjne funkcje przynależności zbioru wyjściowego B(y) oceny niezawodności kombajnu A*



Source: own work / Źródło: opracowanie własne

Fig. 6. Accumulated functions of belonging for the output set *B*(y)* in the assessment of reliability of combine harvester *B*
Rys. 6. Akumulacyjne funkcje przynależności zbioru wyjściowego B(y) oceny niezawodności kombajnu B*



Source: own work / Źródło: opracowanie własne

Fig. 7. Accumulated functions of belonging for the output set *B*(y)* in the assessment of reliability of combine harvester *C*
Rys. 7. Akumulacyjne funkcje przynależności zbioru wyjściowego B(y) oceny niezawodności kombajnu C*

5. Concluding remarks

A review of literature, analyses, studies and verification of the developed method assessing reliability of seasonally operated machines make it possible to formulate the following final conclusions:

1. This method provides an objective assessment of reliability of seasonally operated machines, while the numerical value of the determined index I_R includes all significant relevant characteristics. Both material and non-material aspects of machine operation and maintenance may be considered, as inherently related and affecting reliability of machines.
2. In the developed method assessing reliability of seasonally operated machines we used advanced algorithm procedures, based on the theory of fuzzy sets. It facilitates objectivisation of the obtained index I_R, thanks to reducing the linguistic syntheses to a numerical value.
3. The developed method facilitates quantification of reliability for each machines operated seasonally, irrespective of the length of operation period or storage.
4. The method makes it possible to gain insight and implement principles of proper technical servicing of machines, their storage and performance of pre-seasonal and post-season maintenance. Empirical verification of the method and simulation studies supplied information indicating directions of changes in processes of machine operation and maintenance, whose implementation in practice will provide an effective increase in the level of machine reliability.

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